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REPORT R-1675

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FRANKFORD
ARSENAL

EMERGENCY CONTROL
OF BOUNDARY LAYER ON AIRCRAFT WINGS
BY PROPELLANT ENERGY

by

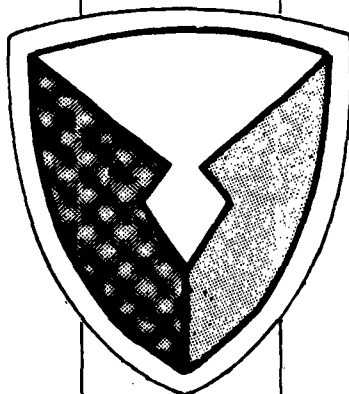A. E. LARSEN
and
C. J. LITZ

ARO(D) Task 5-62

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OF BOUNDARY LAYER ON AIRCRAFT WINGS
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ARO(D) Task 5-62

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FRANKFORD ARSENAL
Philadelphia 37, Pa.
April 1963

FOREWORD

The research work described in this report was performed by Frankford Arsenal, U. S. Army Munitions Command, Philadelphia, Pennsylvania, and was sponsored by the U. S. Army Research Office, Durham, North Carolina. The work was accomplished under Army Research Project Order ARO(D) 5-62 dated 18 December 1961. Dr. Sherwood Githens, Jr., Deputy Chief Scientist of the Army Research Office, was the project officer. The research program was conducted from March 1962 to December 1962 and carried out by the Pitman-Dunn Laboratories, Research and Development Group, under the direction of Mr. Charles J. Litz, Jr., Project Engineer, and Mr. Agnew E. Larsen, Chief Investigator.

Personnel of the Aeronautical Engineering Department, Princeton University, The James Forrestal Research Center (under Contract DA 36-038-SA2-06002), conducted a preliminary study as the aerodynamic part of the subject project. A report covering the results of this study is presented in its entirety in the Appendix. Dr. David C. Hazen, Associate Professor, and Mr. F. Carter Karins, Graduate Student, conducted this study.

ABSTRACT

Operating with the demonstrated and proven state-of-the-art of boundary layer phenomenon as related to airfoils, this project studies two objectives: (1) the uses of safely stored propellant energy instantly released and directed through ducting, ejectors, and/or other means, to appropriately located apertures on the airfoil surfaces and (2) the reattachment of the circulation flow through ballistic-combustion-powered boundary layer control of the airflow over and around stalled airfoil test models.

In pursuit of these objectives, an intensive survey of authoritative literature on boundary layer aerodynamics revealed no previous published interest in the determination of the time interval phenomenon involved in the sequence of airflow events associated with loss of circulation flow and its restoration.

The preliminary research efforts were directed toward the acquisition of time interval data. This was accomplished, in part, by recording and measuring the time interval required for decay of circulation flow with the breakdown of lift in stall, and the measurement of time for the reattachment of circulation flow in the restoration of lift. These experiments were conducted in the smoke flow tunnel of the James Forrestal Research Center of Princeton University. Concurrently, the expenditures of energy involved for restoration of circulation flow were also recorded and measured. These values of transient energy were subsequently utilized by Frankford Arsenal in computations to determine the propellant energy requirements for full scale application of these emergency boundary layer control concepts on the U. S. Army Caribou airplane.

Continuation and expansion of future efforts before full flight tests, both in wind tunnel experiments and in scale model tests of the ballistics aspects, are fully warranted by the results and findings thus far.

TABLE OF CONTENTS

INTRODUCTION

This project employs the concept of using the appropriate performance characteristics of propellant energy to counteract the catastrophic consequences of loss of lift in stall of all types of fixed wing aircraft.

Historical Background

A disproportionately high share of all fatal aircraft accidents occur during the take-off phase of the flight profile (from analyses of records,[1]* approximately 90 percent). In most of these cases the aerodynamic phenomenon involved is stalling. This stall, or sudden loss of lift, is the inevitable consequence resulting from the breakdown of orderly circulation flow over the airfoils. This disasterous situation is the same with all types of fixed wing aircraft.

It should be recognized that the emergency aspects of stall-ing are potentially present in every take-off or landing. Should there be any momentary gusts or maneuver beyond maximum lift, or should there be a reduction of air speed through lowered power during this critical phase of flight operation, a stall or loss of lift will occur. This loss of lift is an aerodynamic consequence caused by a breakdown of the air flow over the wing profile at large angles of attack. This phenomenon, called stall, arises from the separation of boundary layer from the airfoil and is usually accompanied with simultaneous loss of control. Together, these constitute great hazards to flight.

Means for fail-safe reliable recovery from this catastrophic situation in flight have long been sought. Some automatic aero-dynamic means of extending lift at larger angles of attack by re-attachment of flow through the medium of nose slots, either fixed or movable, have been used effectively for years.[2] Likewise, a large school of effort has employed aerodynamic slots in the rear portion of wings, contiguous to the leading edges of the aileron or flaps. The real justification for using these aerodynamic means

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*SEE REFERENCES.

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resides in extending the speed range (i.e., ratio - maximum to minimum speed) of the airplane by reducing take-off and landing speed (slots open) and increasing the top speed at the smaller angles of attack (slots closed).

Discussion

Powered energy sources have been employed, either alone or in conjunction with some of the above aerodynamic means, to extend the lift range or to delay stall. No previous means have used powered energy expressly to reattach the separated airflow to the airfoil in the incipient state of stall. This quick reattachment of airflow is a prime requirement for controllable flight.

Over a period of 17 years, Frankford Arsenal personnel have accumulated a vast experience in developing solid propellant in propellant actuated devices (PAD) for emergency escape of airplane crew members. Using this experience, they have conceived the idea of applying such energy as the primary source for restoration of lift at stall. Thus, through the use of propellant energy, safely stored and ready in propellant actuated devices (such as gas generators), this project proposes to overcome the recognized limitations of known present means in a novel manner - it proposes to transmit this energy through internal ducting to wing and/ or control surface profile apertures at appropriate locations for instant automatic reattachment of the flow by known boundary layer control techniques.

Accordingly, based on this concept, a patent disclosure was issued and, on 11 September 1961, a technical proposal was drafted and forwarded to the Army Research Office - Durham (AROD) for consideration. This proposal was received favorably by them. Subsequently, on 18 December 1961, AROD sponsored and funded their authorization to Frankford Arsenal to study such a device, establishing Research Project No. ARO(D) 5-62, with initiation date of March 1962.

As outlined in this proposal, the task was not to accommodate and implement the escape of the personnel in the low altitude regime of flight profile; rather, it was to enable them to remain with the aircraft and recover it by the use of proven ballistic techniques of PAD in the restoration of full flight lift through reattachment of the boundary layer. This should reduce the accident hazard to both life and aircraft.

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APPLICATION OF PAD ANTISTALL CONCENT
TO THE CARIBOU AIRCRAFT

A contract (DA 36-038-SA2-06002) was awarded to the James Forrestal Research Center, Department of Aeronautical Engineering, Princeton University, to conduct a preliminary study of the rate of growth and decay of blowing-jet-induced circulation on two-dimensional profiles.

Their report (included in this report as the Appendix) represents the first known record of the actual measurement of transient interval of time for circulation flow to breakdown and subsequently be restored on two-dimensional airfoil profiles. These measurements and the visualization of smoke flow phenomenon represent an enlightening examination of separation and reattachment of airflow through control of the boundary layer.

From the results of the Princeton study, the leading edge blowing from the NACA 23015 profile was selected for extending the investigation to a typical Army aircraft. (The NACA 23015 profile is typical of the type used in low speed aircraft, such as transport and cargo carriers.)

It was determined that Frankford Arsenal ballistic engineers would proceed with theoretical investigations of the feasibility of applying the principle of propellant energy as the power source for the full scale restoration of lift on the U. S. Army Caribou aircraft. Studies and computations were made to determine the propellant energy required. Then, a PAD Gas Generator capable of supplying the working fluid for operation of the antistall device was investigated for this aircraft. In short, the object of this study was to determine an order of magnitude in determining the PAD requirements necessary to restore lift to a stalled aircraft, not to design an optimum PAD gas generator.

The following empirical method was used to estimate the amount of solid propellant required to apply the PAD antistall system to the Caribou.

The flow momentum coefficient equation (page 31) was used to compute the jet thrust (using nitrogen gas) required at the

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leading edge slot of the Caribou wing to restore the circulation flow about an airfoil for a take-off speed of 65 mph (V_o, free stream velocity of 95.4 fps). The free stream density, ρ_o, was assumed to be that of air at standard temperature and pressure (STP). The wing area over which the jet is acting, S, was taken as 2/3 that of the total wing area of the Caribou (912 ft^2).* The value for the flow momentum coefficient, C_μ, was taken as 0.047 (see Appendix).

$$C_\mu = \frac{\left(\frac{w}{g}\right) V_j}{\frac{1}{2}\rho_o V_o{}^2 S}$$

where V_j = jet velocity at the slot, fps.

$\quad$ w = mass flow through the slot, lb/sec.

$\frac{w}{g} V_j$ = jet thrust at the slot, lb.

$\quad \rho_o$ = free stream density, slug/ft^3 (0.00237).

$\quad V_o$ = free stream velocity, fps (95.4).

$\quad$ S = wing area over which the jet is acting, ft^2 (600).

$$0.047 = \frac{\text{jet thrust at slot, lb}}{1/2\ (0.00237)\ (95.4)^2\ 600}$$

jet thrust at slot = 304 lb$_f$.

In determining the time of operation for the PAD gas generator, it is necessary to consider two values: reattach flow and sustain flow.

(a) Reattach Flow - the time interval required to reattach the airflow about the airfoil. The impulse is:

$$F_t = 304\ (.5)$$

$$= 125\ \text{lb}_f\text{-sec.}$$

*Caribou values taken from Reference 3.

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(b) **Sustain Flow** - the time interval required to enable the pilot to make corrective actions to restore the aircraft to normal flight. Thus, the PAD generator, in addition to supplying gas for sufficient time to re-establish flow, must maintain this condition of sustained flow long enough for the resumption of normal controllable flight. The impulse is:

$$F_t = 304 \ (30)$$

$$= 9120 \ lb_f\text{-sec.}$$

A time cycle of 0.5 second was used in the computations to determine the propellant requirement for reattachment of flow. Similarly, a time cycle of 30 seconds was assumed and used in the determination of the propellant requirement for the sustained flow.

The weight of propellant required to develop the equivalent thrust was determined empirically. Ammonium nitrate composite type propellant, selected for this study, has a specific impulse, I_{sp}, of $180 \ \dfrac{lb_f\text{-sec}}{lb_m}$. Thus, the equivalent amount of solid propellant is:

(a) **Reattach Flow** -

$$W_p \ = \ \frac{F_t}{I_{sp}} \ = \ \frac{152}{180} \ = 0.842 \ lb_m$$

where W_p = weight of propellant, lb_m

$\quad F_t$ = impulse, $lb_f\text{-sec}$

$\quad I_{sp}$ = specific impulse, $\dfrac{lb_m\text{-sec}}{lb_f}$

(b) **Sustain Flow** -

$$W_p = \frac{9120}{180} = 50.5 \ lb_m$$

A charge adjustment will have to be made to compensate for heat losses.

The solid propellant selected is of the ammonium nitrate composite type (NH_4NO_3). This type of propellant has a relatively cool burning temperature. The products of combustion are smoke-free, relatively noncrosive, noncorrosive, and nontoxic.[4] Ammonium nitrate composite base propellants have been used in such systems as airplane starter cartridges,[5] spin motors,[6] and pressurization units for guided missile systems.[7]

The configuration of the propellant can be established from the combined operating time (30.5 sec), propellant density (0.053 $lb_m/in.^3$) and total charge weight (51.34 lb_m).

The size of the PAD gas generator (pressure vessel) required can be determined by considering the type of ignition, amount of propellant, burning time, and peak operating pressure.[8]

In operation of aircraft, when most stalls occur in the take-off condition, a gust causes one wing to rise or fall and one control surface to lose response before the other, inducing a spin from the unsymmetrical loading.

The mass-moment-of-inertia of the aircraft (particularly for large carriers like the Caribou) tends to delay or prevent an immediate response. However, once roll is induced, the mass-moment-of-inertia of the aircraft tends to keep the roll going, necessitating sufficient altitude to enable the pilot's normal control adjustment to counteract the roll. If sufficient altitude is lacking, the uncontrolled aircraft will strike the ground disastrously.

The use of a propellant energy antistall system works in conjunction with the mass-moment-of-inertia of the aircraft, whose momentum creates the equivalent relative motion of the free stream velocity. This sequence of events facilitates the PAD system's functioning in the incipient stage of loss-of-lift. Thus, the forward momentum of the aircraft is an essential prerequisite as used in conjunction with the PAD boundary layer control system. The unceasing forward motion of the aircraft, if caught in sufficient time to prevent becoming circular or unsymmetrical, either in roll or pitch, assures the equivalent of the free stream velocity. This continuity of air flow about the airfoil functions, together with the propellant gas from the PAD antistall system, in reattaching the separated flow through boundary layer control.

Artist concepts of the PAD antistall and its application to the Caribou are presented in Sketches 1, 2, and 3.

In Sketch 1, it is noted that the stalled condition arises at either take-off or landing. This is so since the lift of an aircraft wing in normal flight is dependent on the relative flow of air over its surface as the aircraft is propelled forward (Sketch 2A). When the velocity of the aircraft is decreased, however, the attack of the airfoil must be increased in order to maintain the required amount of lift. If the velocity of the aircraft decreases to a point where an increase in the angle of attack no longer results in sufficient lift, stalling is encountered. At this angle of attack, the resulting turbulence has destroyed the circulation flow of air (Sketch 2B), resulting in loss of lift. The PAD antistall system functions instantly to maintain a smooth circulation flow of air (Sketch 2C) when the angle of attack approaches the maximum and stall is imminent or actual.

In operation of an antistall system, air is instantly drawn in through perforations distributed about the upper surface of the airfoil or blown out at either the leading (Sketch 3) or trailing edges. The antistall system causes the circulation flow to be reattached, or adhered, to the upper surface of the airfoil.

As a result, therefore, this study offers a means of reducing the hazards of stalling during the critical phases of flight profile in take-off and landing.

CONCLUSIONS

On the basis of the investigation performed with the PAD antistall project, an important and almost completely unknown segment of aerodynamics has been discovered. Thus, the basic concept as presented in Frankford Arsenal proposal (ARO(D) 5-62) has been removed from the realm of abstractness.

Based on the studies as outlined in this report, the amount of solid propellant needed to reattach the circulation flow about a stalled airfoil (Caribou) at take-off, in an effort to save both the

[STALLED CONDITION ARISES AT TAKE OFF OR LANDING]

TAKE OFF

GROUND

LANDING

GROUND
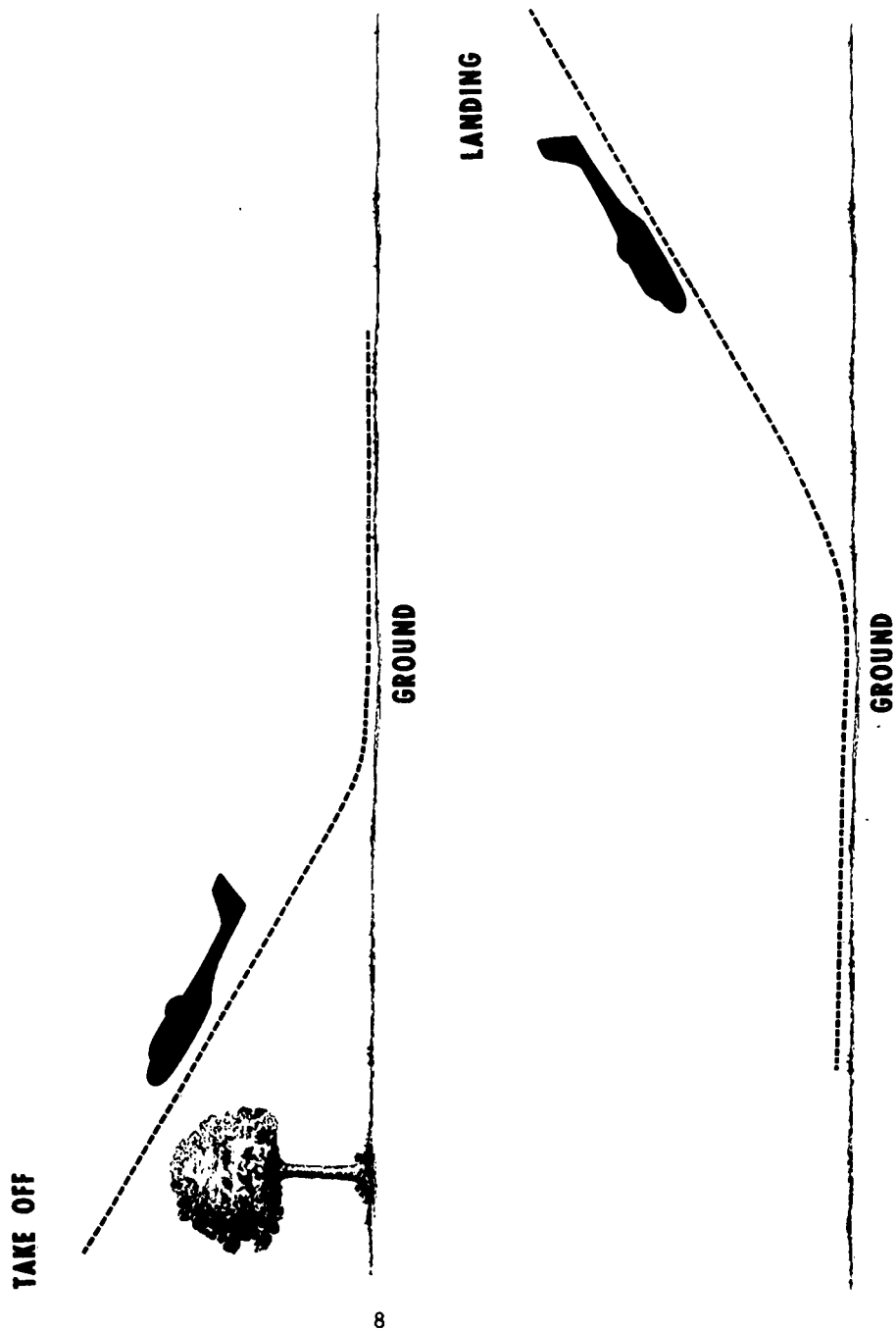
Sketch 1. PAD Antistall Applied to the Caribou

A. AIRFOIL IN NORMAL FLIGHT

B. AIRFOIL IN STALLED CONDITION

C. AIRFOIL USING PAD ANTI STALL CONCEPT
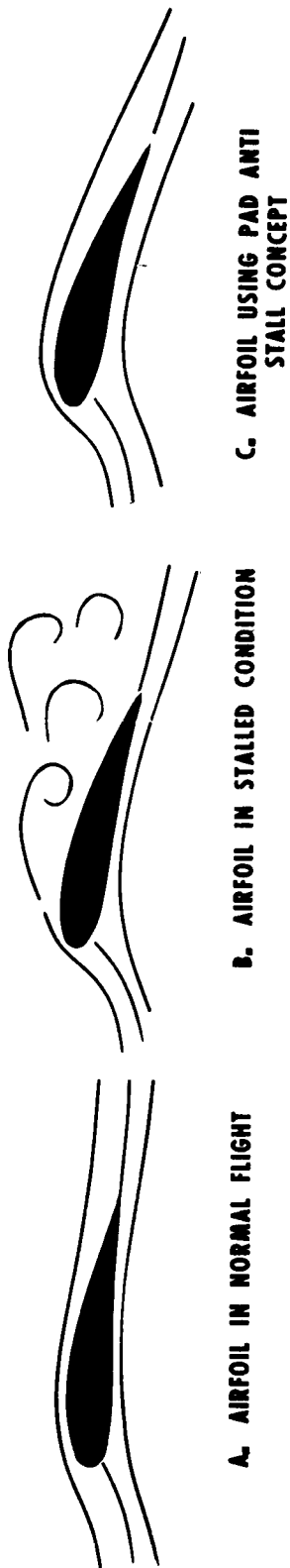
Sketch 2. Emergency Control of Boundary Layer on Airfoil Wing by Propellant Energy

[LEADING EDGE BLOWING SHOWN]

AIRFOIL

GAS PORTS

PAD GAS GENERATOR

Sketch 3. Airfoil with PAD Antistall Unit

pilot and the aircraft, is in the order of 0.842 lb. The amount of propellant required to sustain the reattached flow long enough to enable the pilot to control and maneuver the aircraft into normal flight is in the order of 50.5 lb. These values of propellant have a significant meaning when compared to those required to eject the pilot; e.g., the M8 rocket catapult has a 6.3-lb grain and the XM7 has a 30-lb grain.
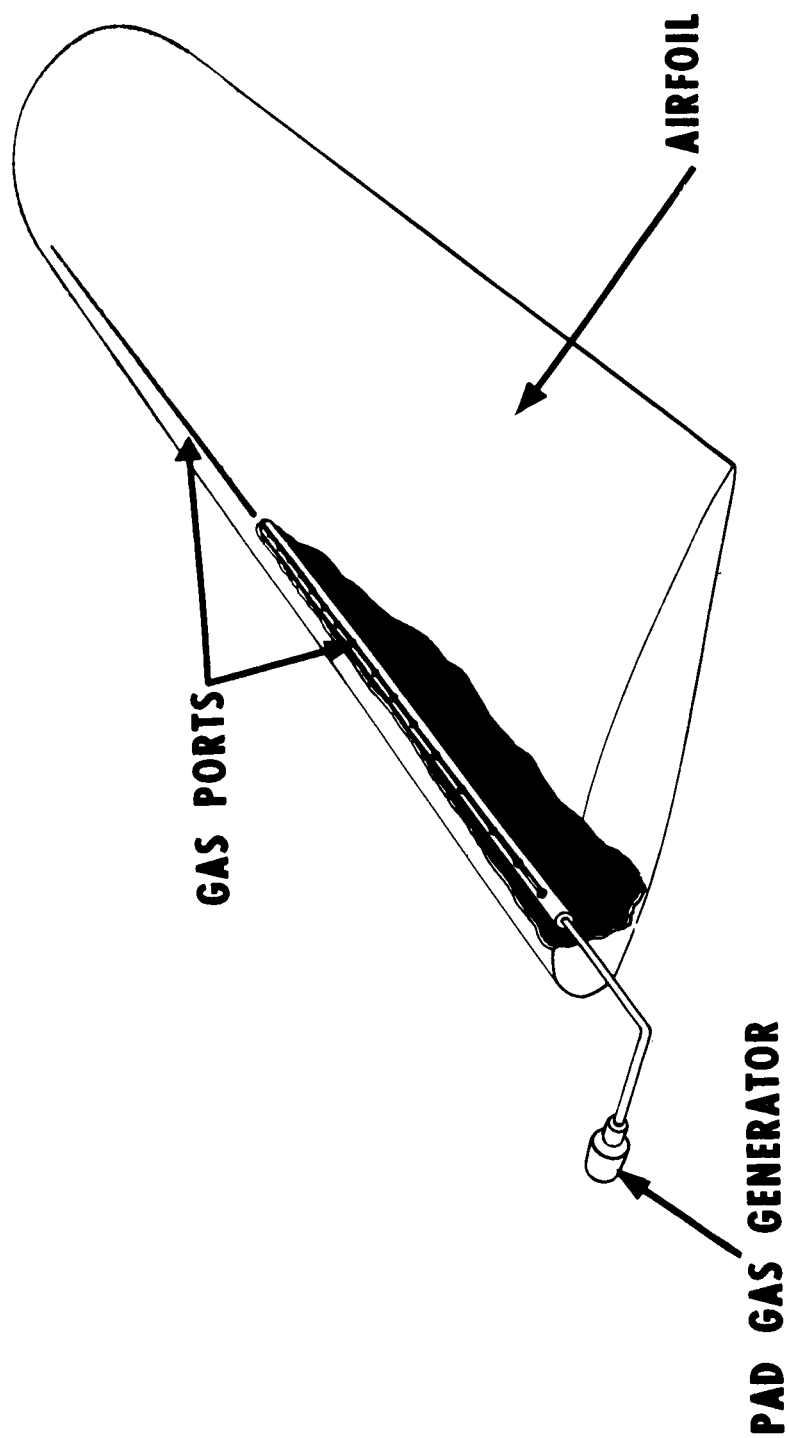
RECOMMENDATIONS

It is recommended that studies be continued to include PAD gas generator design and testing. Such a program would include the following three-phase testing sequence.

Phase I - Smoke Tunnel. The smoke tunnel would be used for a specific airfoil profile to cover a range of angles of attack. A scale model of the PAD antistall system would be evaluated in the smoke tunnel.

Phase II - Wind Tunnel. The wind tunnel would be used for larger airfoil profiles to cover a range of angles of attack with a full scale model of the PAD antistall unit. This phase would permit a study of flow techniques on the full scale model simulating flight conditions.

Phase III - Flight Tests. The aircraft wings of a test aircraft would be mounted with a 4-foot span section of the PAD antistall system. The system would be evaluated under full flight conditions where stall is actually induced. Use of pressure transducers and time reference cameras will be used to record a time plot of the response of the aircraft. For this test, the PAD antistall unit would be mounted on the external surface of the airfoil.

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        NACA RM L51K15   NACA RM A50H09
        NACA RM A51J24   NACA RM A50K06
        NACA RM A9D29   NACA RM L54L21
        NACA RM A52L16a   NACA RM A55K14
        NACA RM A53E06   NACA RM A55K29
        NACA RM A55I09   NACA RM A56G30
        NACA RM L9B11   NACA TN 2847
        NACA RM L51B23   NACA TN 3963
        NACA RM L52L05   NACA Report 1276
    David Taylor Model Basin, Carderock, Md.-
                                TED No. TMB AD-3155
    Naval Air Test Center, Pautuxent, Md. -
                                TED No. PTR AD-349

    In addition, many other authoritative treatments, as
published by NACA and other sources (NASA, RAE, NATO, ARAD,
etc.) were perused objectively.

APPENDIX

A PRELIMINARY STUDY OF THE RATE OF GROWTH AND
DECAY OF BLOWING-JET-INDUCED CIRCULATION
ON TWO-DIMENSIONAL PROFILES

PRINCETON UNIVERSITY
Department of Aeronautical Engineering

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BIBLIOGRAPHICAL CONTROL SHEET

1. __Originating agency and monitoring agency__:

   O.A.: Princeton University, Princeton, New Jersey.
   M.A.: U. S. Army Ordnance Frankford Arsenal, Philadelphia, Penna.

2. __Originating agency report number__: Aeronautical Engineering Department Report No. 632.

3. __Title and classification of title__: A Preliminary Study of the Rate of Growth and Decay of Blowing-Jet-Induced Circulation on Two-Dimensional Profiles. (Unclassified)

4. __Personal authors__: Hazen, D. C., and Karins, F. C.

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12. __Abstract__:

High speed motion picture photography was utilized to study the rate of change of the two-dimensional smoke flow patterns about airfoils produced by the application of boundary layer control by blowing. The times required for circulation build-up after blowing jet initiation and for circulation decay after blowing jet cessation were determined.

SUMMARY

High speed motion picture photography was utilized to study
the rate of change of the two-dimensional smoke flow patterns about air-
foils produced by the application of tangential blowing jets at various
locations on their upper surfaces. Two airfoils, an NACA 23015 and an
NACA 65006, were employed for the tests because of the difference in their
stall patterns at the Reynold's numbers studied, one displaying a typical
trailing edge separation, the other a short bubble-type leading edge
separation.

Tests were made at various angles of attack, blowing momentum
coefficients, free stream velocities, and model configurations. The times
required for circulation build-up after blowing jet initiation and for
circulation decay after blowing jet cessation were determined. The meas-
urements were not detailed enough to separate all of the factors affect-
ing the rates of change, but the major variables were identified.

INTRODUCTION

At the request of representatives of the U. S. Army's Frankford Arsenal, a preliminary investigation of the factors affecting the rate of time required for the build-up or decay of profile circulation induced by surface blowing jets was undertaken. The arrangements studied were typical of many that have been proposed for high-lift boundary layer or circulation control. The purpose of the investigation was to obtain order of magnitude information with which to evaluate the feasibility of a proposed emergency system designed to re-establish the flow about a profile that had suffered either inadvertant stall or powered lifting device failure.

The method selected to obtain the desired information rapidly and economically utilized the 2" x 36" Two-Dimensional Smoke Tunnel of the Subsonic Aerodynamics Laboratory of Princeton University's Department of Aeronautical Engineering. The models were placed in this tunnel at fixed angles of attack and the change in the smoke flow patterns produced as a blowing jet was turned on or off was photographed with a 16 mm Wollensak Fastax high speed motion picture camera. The resulting movies were then analyzed frame by frame to obtain the desired information.

Two entirely different types of airfoils were employed, an NACA 23015 displaying a trailing edge stall, and an NACA 65006 displaying a short bubble leading edge stall. Both were equipped with .20-chord plain flaps and blowing shots located near the leading edge and at the flap hinge line.

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Since the main interest of this exploratory investigation was centered on the flow patterns resulting when the wing was operating at angles of attack above which it would normally be stalled without the application of boundary layer control, a large percentage of the tests were conducted at relatively high angles of attack. The boundary layer control system employed on the NACA 23015 profile could, because of the large nose radius of the section, attach the flow even if the stall angle were exceeded by 5 or more degrees. The NACA 65006, having a considerably smaller nose radius, could not be reattached at angles much greater than 1 or 2 degrees above its stall.

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EXPERIMENTAL EQUIPMENT

Smoke Tunnel

The wind tunnel employed for these studies was the Princeton University 2" x 36" Smoke Tunnel. This tunnel, which is described in detail in Reference 1, is capable of speeds up to about 80 feet per sec. with good streamline resolution. Owing to model and blowing supply limitations, however, the maximum speed for these tests was restricted to 60 ft. per sec.

Airfoil Sections

The two airfoil sections employed are shown in Figure 1. Each had a sixteen-inch chord and two-inch span. They were constructed of mahogany and Plexiglas and were equipped with 0.20-chord plain flaps. Blowing slots were located .02-chord aft of the leading edge and at the flap break.

The interior of each profile was designed to serve as a plenum chamber in the pressure system of the blowing jet. A static pressure tap located in this plenum chamber provided a means of measuring either the static pressure at the blowing slot when the pressure supply was turned off or the stagnation pressure of the gas ejected from the slot when the pressure supply was turned on.

Pressure System

The gas supply for the blowing jet consisted of a cylinder of compressed nitrogen, a reducing valve, an electrically operated shut-off

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3⅝

5/8 O.D. pipe
¼ O.D static pressure pick–up

0.025

1.547

0.035

$A_j = \left(\dfrac{.035 + .025}{2}\right)(1.547) = 0.0464 \text{ sq. in.}$

TRAILING EDGE SLOT AREA

16 in.

1 3/8

6 ¼

3/8

S = Wing area = 16(1.563) = 25.01 sq. in.

2 in.

1 ½

1/4

0.043

1.563

$A_j = \text{Slot area} = (.043 \times 1.563) = 0.0672 \text{ sq. in.}$

LEADING EDGE SLOT AREA

FIGURE IA.   MODEL NO. I – NACA 23015 WITH .20c PLAIN FLAP

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A_j = Slot area = (.015)(1.565) = 0.0235 sq.in.

LEADING EDGE SLOT AREA

A_j = (.021)(1.585) = 0.0333 sq.in.

TRAILING EDGE SLOT AREA

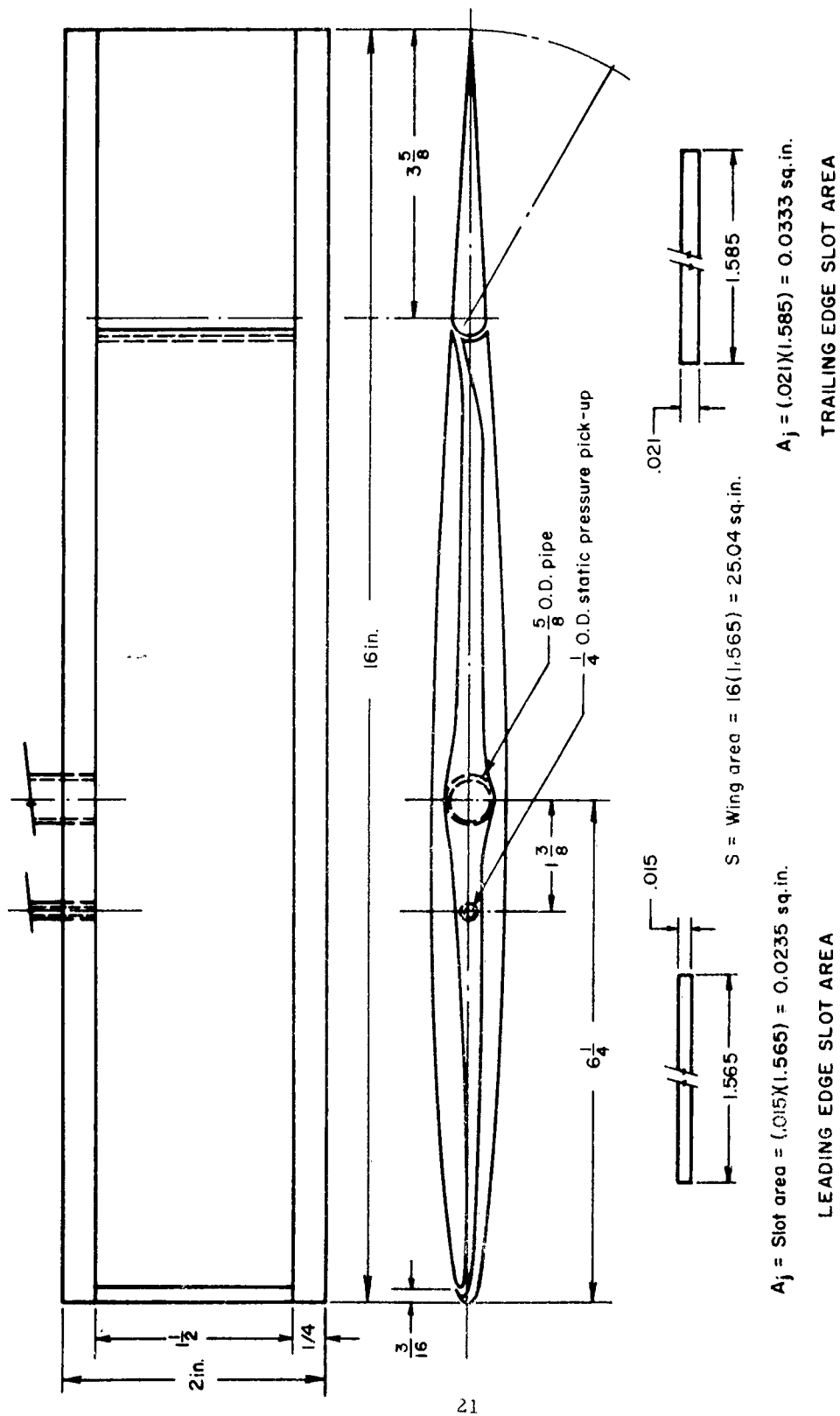S = Wing area = 16(1.565) = 25.04 sq.in.

FIGURE 1B.   MODEL NO. - NACA 65006 WITH .20c PLAIN FLAP

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valve, and the associated piping necessary to connect the tank to the model. Nitrogen was used as the gas in the pressure system because, being inert, it would not react with the vaporized kerosene used to produce the smoke streamlines in the tunnel.

A pressure reducing valve lowered the pressure from 1500 psi at the supply tank to the 0 - 6 psi range at which the experiments were conducted. An electrical solenoid valve provided a means of rapidly opening and closing the supply line to the plenum chamber in the model. The operation of the solenoid was controlled by a timer connected to the Wollensak Fastex camera which photographed the sequence of events at rates up to 4,000 frames per second. The timer was adjusted either to open or close the valve as required at a time sufficiently delayed after the start of the camera to have permitted the film to come up to speed, but rapidly enough to record the full change in circulation. The valve itself was placed as close as possible to the plenum chamber in order to reduce the time lag of the system.

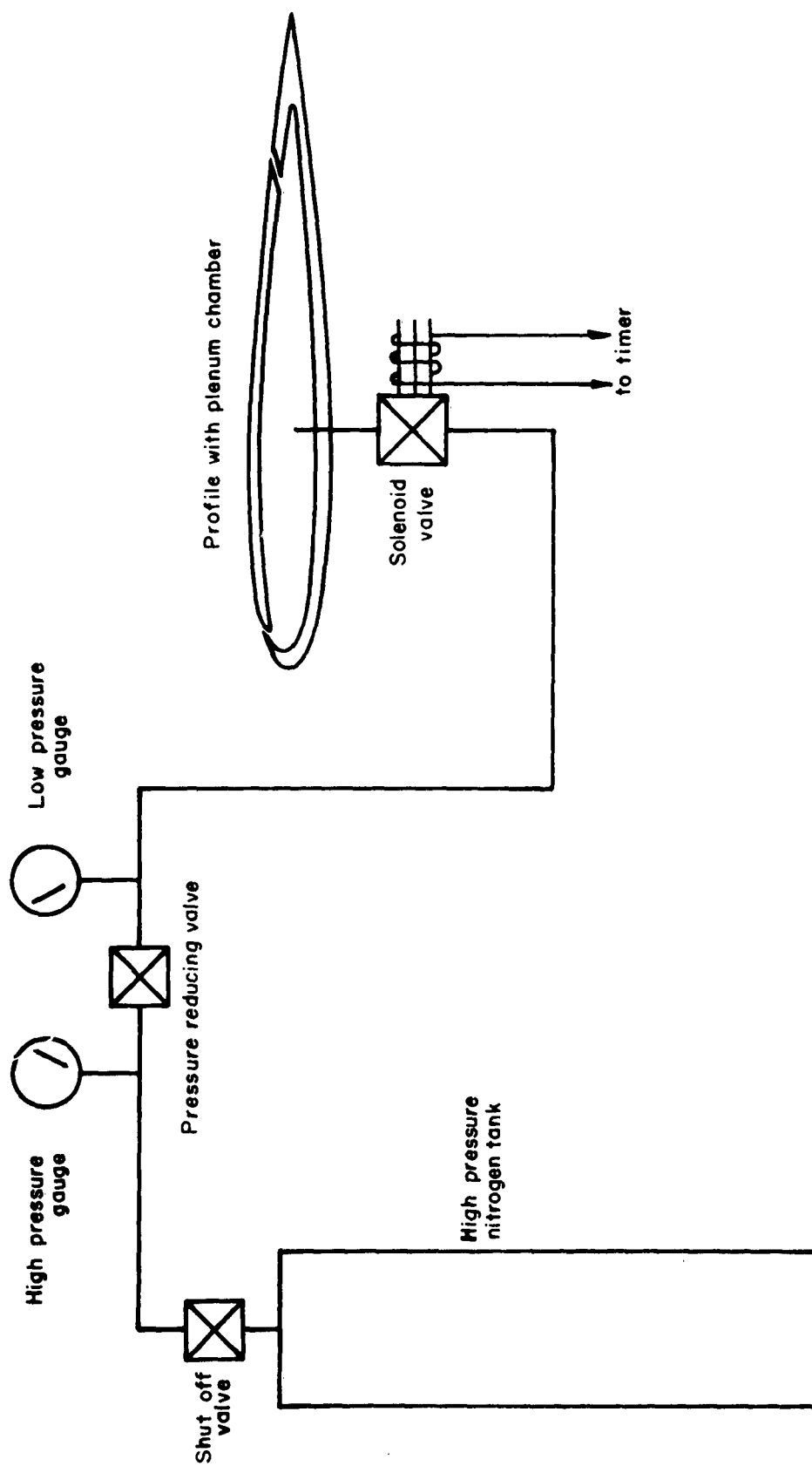The pressure system is shown schematically in Figure 2.

Profile with plenum chamber

Solenoid valve

to timer

Low pressure gauge

High pressure gauge

Pressure reducing valve

High pressure nitrogen tank

Shut off valve

FIGURE 2. BLOWING JET PRESSURE SYSTEM

DATA RECORDING

The two-dimensional lift coefficient at any given instant served as a means of determining the relative magnitude of the circulation. The lift coefficient was determined by the method of stream-line displacement described in Reference 2. The variation of lift coefficient as a function of the angle of attack for the given airfoils was obtained from Reference 3 and then correlated with streamline displacement data for the particular models used in this investigation. The calibration curves so obtained were then extrapolated to the angles of attack at which the tests were made.

This extrapolation, admittedly a dubious procedure, was necessary both because many of the tests were made at angles of attack at which the profiles were operating in a stalled condition and because the lift coefficients obtained by use of the blowing jet were considerably greater than the maximum lift coefficient given in the literature for the basic profiles.

In order to determine the time history of the circulation as the blowing jet was either started or stopped, all that was required was the streamline displacement at any given instant. Since the effects studied were of a transient nature, the instantaneous streamline displacements as events proceeded were recorded by means of high-speed motion picture photography.

The time required to change the circulation from one value to another was assumed to be the time interval between the start or stop

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of the blowing jet and the time at which the leading-edge stagnation point reached a new point of equilibrium. The time at which the jet started or stopped was recorded by means of a pressure transducer connected to the static pressure tap in the plenum chamber of the airfoil. Signals from the transducer were amplified and then recorded on a Sanborn recorder.

The Wollensak Fastex camera, used to make the high-speed motion pictures of the event, was equipped with a timing light driven by a signal generator recording time intervals of one thousandth, 0.001, second on the edge of the film. The time scales on the Sanborn recorder and the motion picture film were correlated by means of a flash gun and light meter arrangement. The signal produced by the light flash triggered by the circuit controlling the operation of the solenoid was amplified and then recorded on the Sanborn recorder. Thus the light from the flash gun was recorded on the film and simultaneously, the impulse from the light meter was recorded with the pressure data on the Sanborn multi-channel recorder.

It was not possible to obtain quantitative pressure data from the pressure transducer because the unit used required a harmonic filter in the amplifier circuit that was not available. Therefore, the pressure data were used only as a qualitative indicator of the system pressure. Quantitative pressure data were obtained by use of a "U" tube manometer, and therefore only the steady-state pressures in the plenum chamber could be measured.

Because of the nature of the devices employed in the data recording sequence, a period of time elapsed between the signal and the

actual initiation of the jet. Further time elapsed before steady jet con-
ditions could be established. These times are all included in the mea-
sured time required to bring the forward stagnation point to equilibrium.
A number of calibration procedures were tried, but within the instrumenta-
tion limitations of this preliminary study, no successful techniques of
accurately evaluating these effects and subtracting them from the total
time was found. The times measured for the circulation build-up and de-
cay are thus probably conservative, although a definite statement cannot
be made until more information comparing the time required to establish
the model jet with the time required to establish a similar full-scale
jet can be obtained.

Figure 3 presents photographs of the experimental arrangement.
The surveyer's transit was used to determine the steady state streamline
displacements as accurately as possible. Figure 4 is a slightly enlarged
photograph of a typical 16 mm strip of test film showing the timing marks
on the side.

(a) Fastex camera (c) Pressure transducer amplifier

(b) Sanborn recorder (d) Transit

DATA RECORDING EQUIPMENT

(e) Smoke tunnel test section (h) manometer

(f) Model (i) Signal generator for timing
            marks on film

(g) Nitrogen bottle

         (j) Time sequence control

         (k) Fastex camera

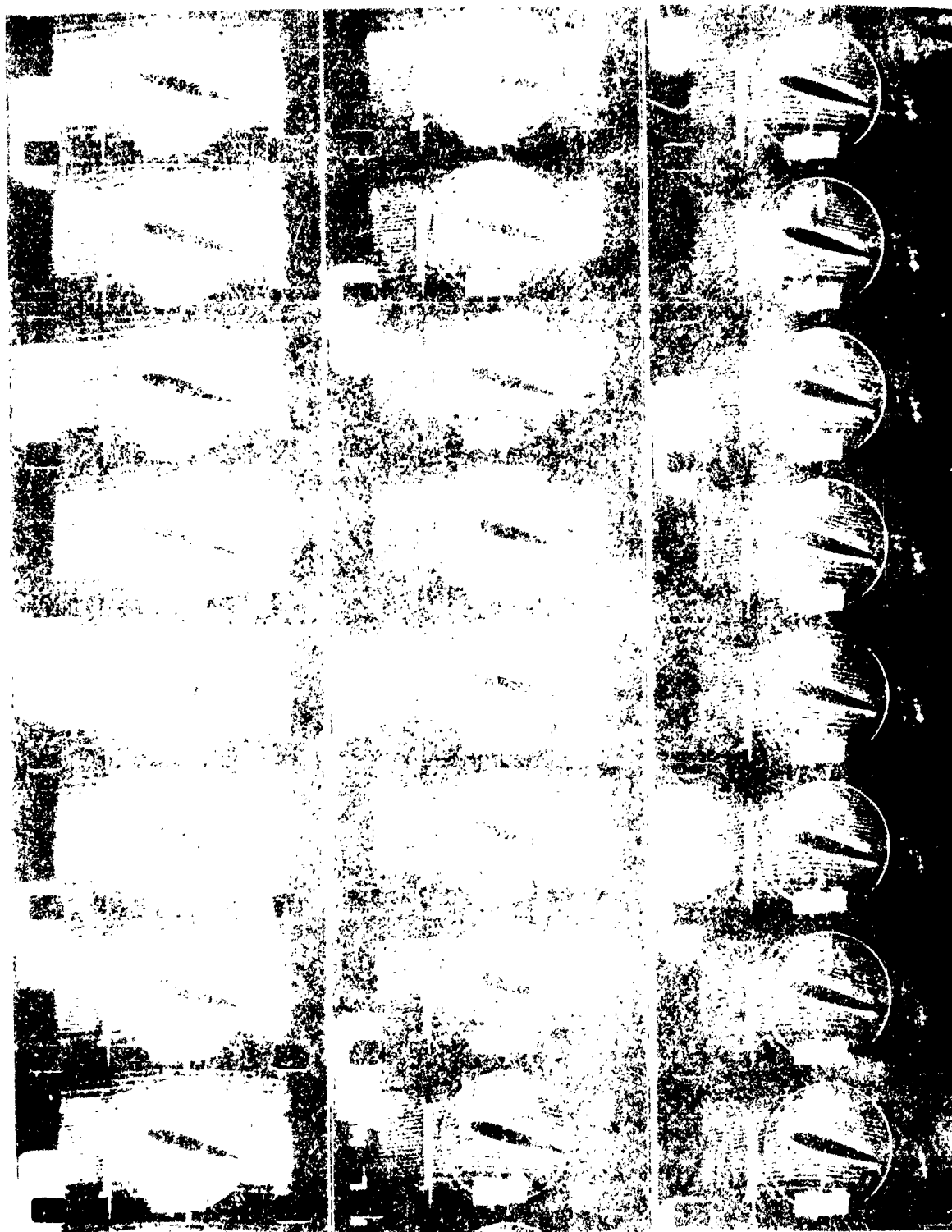SMOKE TUNNEL TEST EQUIPMENT

FIGURE 3

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FIGURE 4. TYPICAL TEST FILM

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TEST PROGRAM

The objectives of any preliminary investigation are generally
to obtain order of magnitude solutions under conditions of both limited
time and money. More specifically, the objectives of this study were
to determine the suitability of the test techniques, and to obtain so
far as these test techniques permitted, information relating to the length
of time required to establish or destroy flow patterns associated with a
powered boundary layer control system.

Although the problem of the length of time required to create
or destroy a given circulation is a general one, with applications rang-
ing from the fields of gust alleviation to flutter, the particular concern
in this case was with the development of a safety system designed to over-
come the separated flow associated with either an inadvertent stall of
an unpowered wing or the abrupt cessation of a powered BLC system. In
either case, the profile would probably be operating in an angle of at-
tack range well above that required for $C_{l_{max}}$ of the basic uncontrolled
wing.

Because of the large variation in the nature of profile stall,
two typical sections having very different stall characteristics were
selected. The first was an NACA 23013 section. This section is 15% thick
and stalls, in the Reynolds Number range of interest, as result of a sepa-
ration of the turbulent boundary layer starting at the trailing edge and
moving forward. The second profile was of an NACA 65006 section which
characteristically displays an abrupt separation from the leading edge.

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For this preliminary study, it was decided that in order to hold the number of variables within bounds, the angle of attack would not be changed during the process of the build-up or decay of circulation, but would be held at an arbitrarily selected constant value. In the actual case, of course, a sudden loss or gain of lift would produce a dynamic response of the aircraft and a resultant change in angle of attack. Since this change would be a function of the particular type of aircraft under consideration, it was decided to defer an investigation of the influence of the rate of change of angle of attack until a later program.

The procedure followed was to set the wing at an angle of attack of interest and to adjust the powered boundary layer control as desired, defining its operation by the flow momentum coefficient. This momentum coefficient, C_μ, is used to relate the slot flow to the resultant degree of circulation control provided, assuming a fixed profile geometry, angle of attack, location and alignment of the powered device, and constant free stream conditions. The flow momentum coefficient came into general usage in the literature after theoretical and experimental work had revealed that a term based on flow volume alone was not suitable for the desired jet situation.

The blowing jet cannot be simulated by a source, but acts rather as a series of sinks distributed along a thin membrane. The basis for the parameter C_μ is the thrust of the jet at the slot. It is found that, where the operation is primarily that of altering the potential flow pattern, this term is unique, but it becomes less rigorous where merely

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controlling the viscous boundary layer to avoid separation is the major

effect. (In practice, C_μ yields good correlation for trailing-edge

systems. Its value for use with leading-edge systems has, however, not

yet been fully established.)

C_μ is defined by non-dimensionalizing the jet thrust as follows:

$$C_\mu = \frac{(w/g)\ V_j}{1/2\ \rho_o\ V_o^2\ S}$$

where:

V_j = jet velocity at the slot, ft/sec.

w = mass flow through the slot, lbs/sec.

$(w/g)\ V_j$ = jet thrust at the slot, lbs.

ρ_o = free stream density, slugs/ft^3

V_o = free stream velocity, ft/sec

S = wing area over which the jet is acting, ft^2

Some investigators feel that, where the blowing slot is located

well forward of the trailing edge, it is more convenient and just as real-

istic to use the ratio of the jet velocity at the slot to the infinite free

stream velocity, V_j/V_o, rather than the flow momentum coefficient, C_μ

(Reference 4).

In order to put the equation for C_μ in more useful form, the

following expression for w_j is substituted into the original equation:

$$w_j = g\ \rho_j A_j V_j$$

where:

g = acceleration of gravity, 32.2 ft/sec^2

ρ_j = jet density, slug /ft^3

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A_j = jet slot area, ft^2

V_j = jet velocity, ft/sec.

The resulting expression is then:

$$C_\mu = \frac{\rho_j A_j V_j^2}{1/2 \, \rho_0 V_0^2 \, S}$$

This equation can be further simplified if it is noted that for the velocities involved, $\rho_j/\rho_0 \approx 1$. This simplification is valid, even considering the use of pure nitrogen in the jet, because the jet and free stream velocities are relatively so low that any difference in densities can be neglected. The final form of the equation is then:

$$C_\mu = \frac{2A_j}{S} \left(\frac{V_j}{V_0} \right)^2$$

Bernoulli's equation for incompressible flow:

$$P_s + 1/2 \, \rho \, V^2 = P_0$$

was applied between the plenum chamber and the jet slot. The value of the static pressure in the plenum chamber, when the pressure system was turned off, was assumed to be the static pressure into which the jet was exhausted. Since, for all practical purposes, the nitrogen in the plenum chamber was at the stagnation condition when the jet was operating, the value of the static pressure in the plenum chamber when the pressure system was turned on was the steady state stagnation pressure of the gas ejected from the slot. The equation for the jet velocity is thus:

$$V_j = [\, 2 \, (P_0 - P_s)/\rho_j \,]^{1/2}$$

where:

V_j = jet velocity, ft/sec

P_0 = plenum chamber static pressure with the jet operating, lbs/ft^2

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p_s = plenum chamber static pressure with the jet off, lbs/ft^2

p_j = jet density, slugs/ft^3

The jet density used in the calculation of the jet velocity was that of nitrogen at a temperature of 80°F. and a pressure of one atmosphere. Nitrogen was assumed to behave as a perfect gas under these conditions so that the perfect gas equation holds:

$$\rho = p/RT$$

where:

ρ = density, slug /ft^3

p = pressure, lbs/ft^2

R = gas constant = 1774 ft^2/sec^2 °R for N$_2$

T = temperature, °R

Using the above conditions, the jet density is calculated to be:

$$\rho_j = 0.00221 \text{ slugs/ft}^3$$

ANALYSIS OF EXPERIMENTAL ERROR

In order to determine the degree of accuracy of the experimental data presented in this report, sample values of the data are presented below.

1. Free stream velocity

   calibration error

Total head pressure   static pressure

24.65 ± 0.02 in. H_2O 25.00 ± 0.02 in. H_2O

q = 0.35 ± 0.04 in. H_2O

ρ = 0.002319 slugs/ft^3

Using Bernoulli's equation, the free stream velocity is calculated to be:

$$V_o = 39.6 \pm 2.3 \text{ ft/sec}$$

An additional variation due to the error in the "q" meter readings produced an error of ± 1.0 ft/sec. The drop in the line voltage to the motor generator set caused by the light banks used to illuminate the test section introduced an additional systematic error in the value of the free stream velocity. The maximum change in the "q" meter under these conditions was less than one-tenth (0.10) of a scale division. Therefore, the maximum error resulting was less than 8.35% of the measured free stream velocity. Thus, the total possible error in the measurement of the free stream velocity was ± 16.70%.

Jet velocity Error:

$$q_j = 7.00 \pm .04 \text{ in } H_2O$$

$$\rho_j = 0.00221 \text{ slugs/ft}^3$$

$$V_j = 181.5 \pm 0.5 \text{ ft/sec}$$

The error in the measurement of the jet velocity was $\pm 0.28\%$ of the measured value.

C_μ Error:

The error in the value of C_μ for the example is the sum of the percent errors of V_o and V_j. Therefore, C_μ is known to an accuracy of $\pm 16.98\%$.

Time Error:

In addition to the difficulties discussed previously resulting from unknown time lags in the system, the accuracy of the measurement of the time required to change the circulation was limited by the ability to determine the time at which the streamlines reached equilibrium. This time was determined by measuring the streamline displacement at ten-frame intervals on the data film. Thus, the equilibrium point was determined to an accuracy of ± 10 frames on the motion picture film. This was equivalent to an error in the time measurement of ± 0.005 seconds. An additional error in the time measurement of ± 0.005 seconds was incurred in reading the data trace of the pressure transducer. The systematic error due to the time lag of the pressure sensing and recording equipment was assumed to be also on the order of ± 0.005 seconds. Thus, the total error of the time measurement was ± 0.015 seconds.

C_ℓ Error:

The values of the two-dimensional lift coefficient obtained were used as qualitative measurement only since the accuracy of the

streamline displacement method used to determine these values was unknown when applied to angles well beyond the stall.

The order of magnitude of the possible errors from each source is summarized below.

1. free stream velocity $\pm$ 16.70%

2. jet velocity $\pm$ 0.28%

3. flow momentum coefficient, C_μ $\pm$ 16.98%

4. growth or decay time $\pm$ 0.015 seconds

5. two-dimensional coefficient of lift   unknown

DISCUSSION OF RESULTS

In spite of the limitations on both the quantity and the accuracy of the results obtained, a number of interesting facts emerged from these investigations. The most significant of these is the fact that the time for circulation build-up or decay is a much stronger function of free stream velocity than of the jet velocity, a not too surprising fact since the profile circulation affects the entire flow field not just the region adjacent to the jet.

The data obtained with the NACA 23015 profile are tabulated in Table I. In order to obtain an idea of the phenomena involved, a large number of runs were conducted at an angle of attack of 20° or slightly more than 5° above the basic airfoil stall. Steady state tests indicated that at this angle, the flow could be reattached by blowing through the leading edge slot with a minimum $C_{\mu} = .047$. Employing this value, runs were made at free stream velocities of 20, 40, and 60 ft/sec. At the highest speed, the reattachment, although appearing complete to the eye, was disclosed by the film to be of an unsteady nature, creating some difficulty in the determination of the time to bring the forward stagnation point to rest.

A study of the film disclosed the reattachment process started approximately .01 sec after current was supplied to the solenoid valve. The first effect discernable was the beginning of the formation of a vortex at the jet nozzle exit. This grew rapidly in size, although its exact dimensions were difficult to determine owing to the limited definition

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TABLE I

Model No. 1   NACA 23015

	Run No.	α°	δ_f°	V_o ft/sec	V_j ft/sec	V_o c/sec	T_o sec/c	T sec
1.	5	20	0	20	59.4	15	.0667	.350
2.	4	20	0	40	119.0	30	.0333	.160
3.	6	20	0	60	181.0	45	.0222	.166 .132
4.	9	20	0	40	64.0	30	.0333	.175
5.	10	20	0	40	79.6	30	.0333	.261
6.	15	20	0	40	112.0	30	.0333	.156
7.	16	20	0	40	137.0	30	.0333	.156
8.	17	20	0	40	159.0	30	.0333	.162
9.	20	16	0	20	57.4	15	.0667	.318
10.	18	16	0	40	120.0	30	.0333	.139
11.	19	16	0	60	168.0	45	.0222	.124
12.	7	20	15	40	121.0	30	.0333	.160
13.	8	20	45	40	121.0	30	.0333	.132
14.	12	20	0	20	59.5	15	.0667	.720
15.	11	20	0	40	121.0	30	.0333	.251
16.	13	20	0	60	182.0	45	.0222	.198
17.	23	7.5	15	20	125.0	15	.0667	.117
18.	21	7.5	15	40	246.0	30	.0333	.101
19.	24	7.5	45	20	126.0	15	.0667	.239 ±.020
20.	25	7.5	45	40	245.0	30	.0333	.103
21.	26	7.5	45	60	369.0	45	.0222	.055

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TABLE I (Continued)

	T/T_o	C_μ	L.E.	T.E.	Growth	Decay	Initial C_l	Final C_l	ΔC_l
1.	5.25	.0474	x		x		1.56	2.20	.64
2.	4.81	.0476	x		x		.98	2.24	1.26
3.	7.47 5.93	.0490	x		x		1.58	2.33	.75
4.	5.25	.0137	x		x		1.32	1.32	.00
5.	7.85	.0212	x		x		1.02	1.32	.30
6.	4.69	.0422	x		x		1.42	2.18	.76
7.	4.69	.0631	x		x		1.86	2.16	.30
8.	4.86	.0850	x		x		1.50	2.37	.87
9.	4.78	.0441	x		x		1.50	2.08	.58
10.	4.14	.0484	x		x		1.94	2.37	.46
11.	5.59	.0422	x		x		1.42	2.18	.76
12.	4.81	.0492	x		x		1.38	2.53	1.15
13.	3.96	.0492	x		x		2.00	3.14	1.14
14.	10.70	.0475	x			x	2.08	1.32	.76
15.	7.54	.0492	x			x	2.28	1.15	1.13
16.	8.92	.0495	x			x	2.24	1.32	.92
17.	1.76	.1450		x			1.35	1.64	.29
18.	3.03	.1410		x			1.94	2.04	.10
19.	3.59	.1470		x			2.16	2.45	.29
20.	3.09	.1390		x			2.16	2.45	.29
21.	2.48	.1410		x			2.30	2.53	.23

provided by the spacing of the smoke streams, and began to move down-stream adhering to the upper surface of the profile. The speed of down-stream motion of this vortex appeared to increase with time, although the lack of definition of its core and its rapidly expanding size made this difficult to determine. It is felt that this increase in speed was primarily a reflection of the build up of jet velocity, but it may also have reflected a natural increase in the upper surface flow velocity owing to reattachment.

It is interesting to note that after the passage of this vortex the flow started to attach to the upper surface, but that this fact was not reflected as a motion of the forward stagnation point until the vortex had reached the vicinity of the trailing edge. Once the forward stagnation point started to move, however, as shown by Figure 5, it continued at a roughly constant rate (if small perturbations are neglected) until its final equilibrium position was reached.

It proved impossible to relate the time trace of the pressure orifice within the model to the actual jet build-up. As shown in Figure 5, as the valve started to open, the pressure transducer recorded a pressure drop, probably due to the gas stream rushing past it. As the gas rushed in, filled the plenum, and started to be ejected out the slot, a series of pressure surges were recorded, with steady state conditions not being achieved until after the equilibrium circulation had been reached. Without much more detailed instrumentation, it is impossible even to hazard a guess about the behavior of the jet during this period.
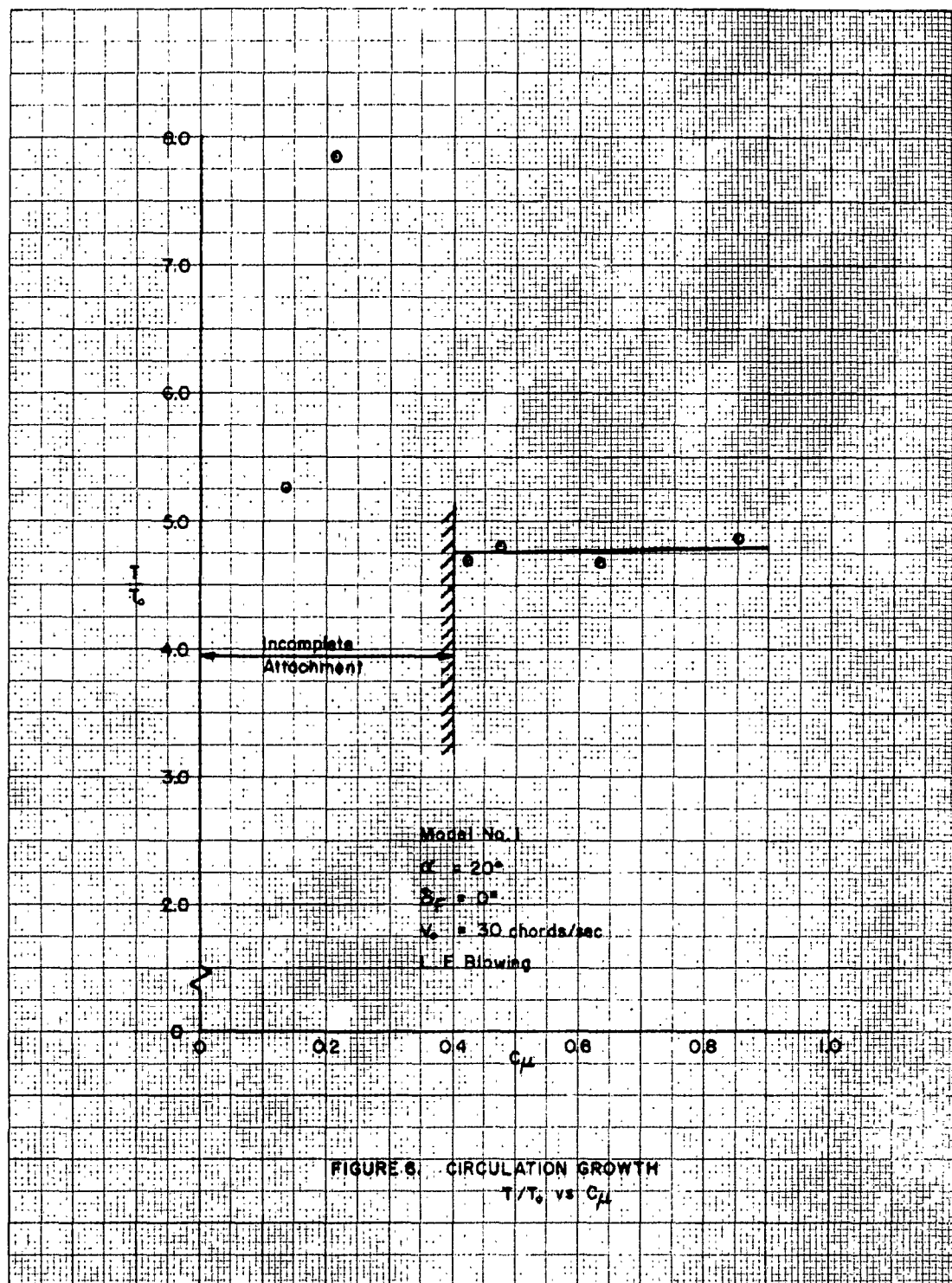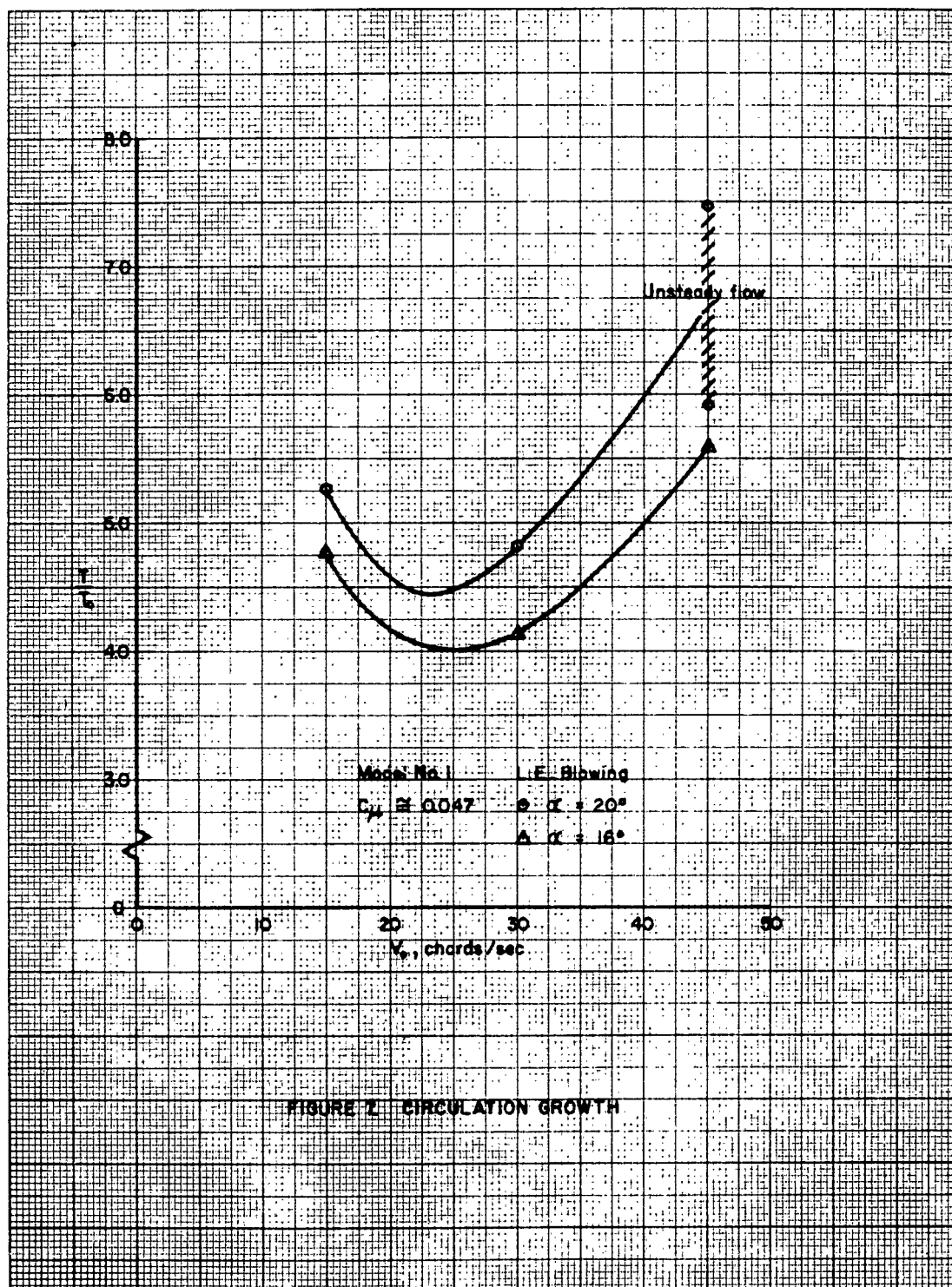
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Figure 5. Circulation Growth

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This inability to define the jet conditions may not be as severe a limitation as it might at first appear. Figure 6 compares the time for complete circulation equilibrium as a function of C_μ. It will be seen that once C_μ was increased sufficiently to achieve essentially complete reattachment of the flow, the time required to reach equilibrium conditions was essentially constant. It is interesting to note, owing to the conditions of these tests, possibly the Reynolds number range, or possibly the close spacing of the wind tunnel walls, and resultant wall boundary layer interference, that, although a C_μ of .049 (Run No. 6) was insufficient to achieve complete attachment of the flow at a speed of 60 ft/sec., a value of .0422 (Run No. 15) accomplished the task at 40 ft/sec.

Changing the extent or the character of the separated area changes the time required for reattachment. Figure 7 is a comparison of the times required to achieve circulation equilibrium at a $C_\mu \approx .047$ for the profile at angles of attack of 20° and 16°, the former being about 5° above stall, the other only 1°. As would be expected, the time required at the lower angle of attack is appreciably shorter than that at 20°.

Because of the strong dependence of the circulation growth time upon the magnitude of the free stream velocity, these data have been presented as plots of the ratio T/T_0, the time required to achieve circulation equilibrium, to the time required for the free stream to travel one chord length, versus the free stream velocity measured in chord lengths per second.
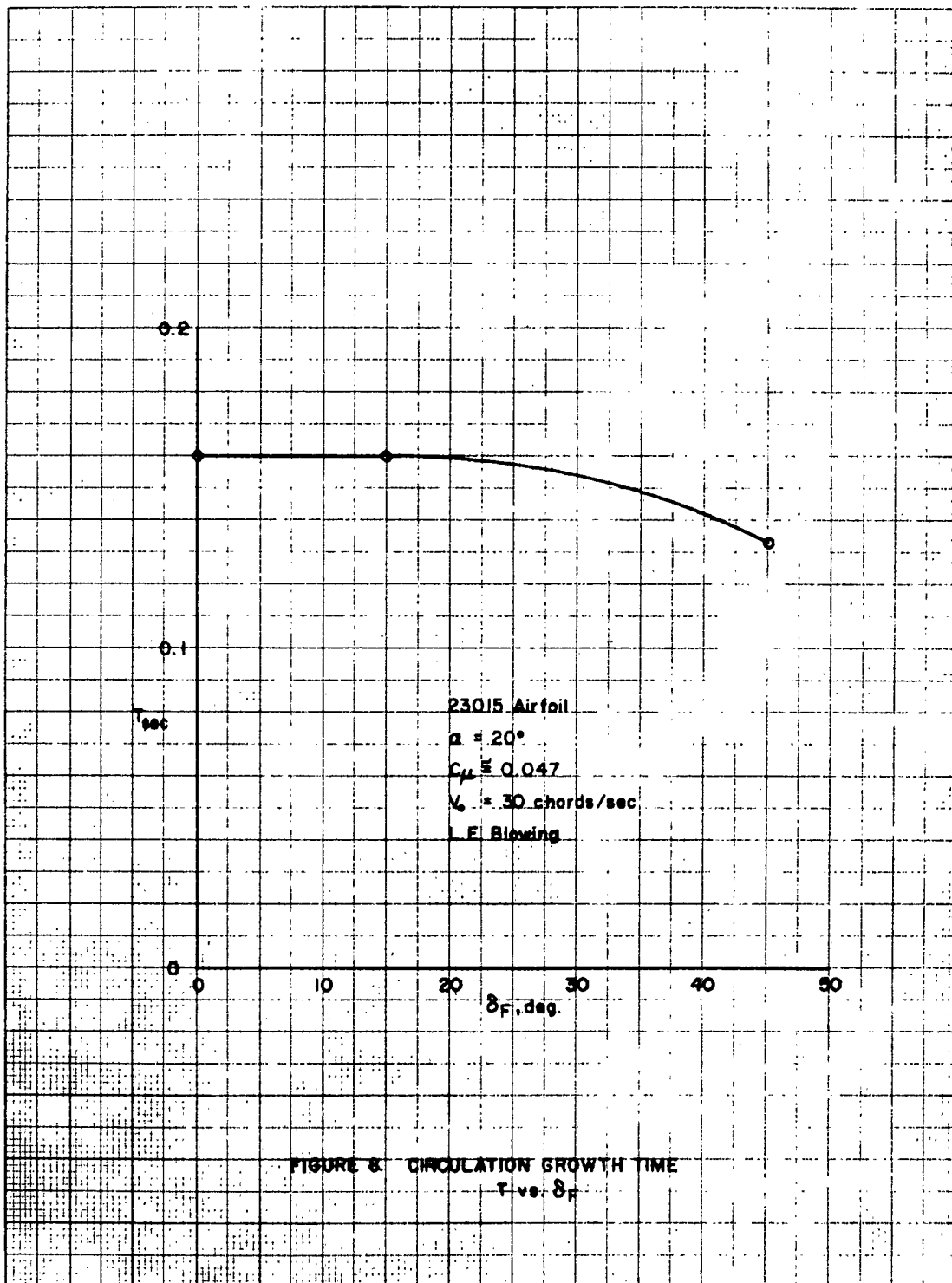
42

FIGURE 6. CIRCULATION GROWTH
T/T_0 vs C_μ

Model No. 1
$\alpha = 20°$
$\delta_F = 0°$
$V_c = 30$ chords/sec
L. E. Blowing

Incomplete Attachment

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FIGURE 2. CIRCULATION GROWTH

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At the present moment there is insufficient information avail-able to speculate about the shape of these curves. Reattachment of a separated flow is a complicated process in which both the viscous and inertial forces within the separated region and the blowing jet play a major role. Thus, although the free stream velocity is a major factor in determining the time it takes for the flow field to react to a change of conditions about the profile, it is by no means the only one.

Deflecting the trailing edge flaps when the profile was at angle of attack of 20° had comparatively little effect upon the time required for circulation growth although, as shown by Figure 8, the surprising result was obtained that deflecting the flap by 45° did produce a reduc-tion in the time required of about .028 seconds. Detailed studies utiliz-ing the streamline deflection method showed that, although the profile went from a c_ℓ of 2.0 to 3.14 for a $\Delta c_\ell = 1.14$ as the leading edge blowing was applied in $\delta_f = 45°$ case, it went from 1.38 to 2.53 for a $\Delta c_\ell = 1.15$ in the $\delta_f = 15°$ case and from .98 to 2.0 for a $\Delta c_\ell = 1.02$ in the flaps-up case. Further examination showed that the extent of the reattached flow was considerably less in the $\delta_f = 40°$ case than for the $\delta_f = 15°$ case, leading to the conclusion that the shorter time required for circulation growth was merely a reflection of the fact that a large part of the highly deflected flap was unaffected by the blowing jet. The result was that the circulation growth acted as if the effective chort of the profile was shorter than its actual chord.
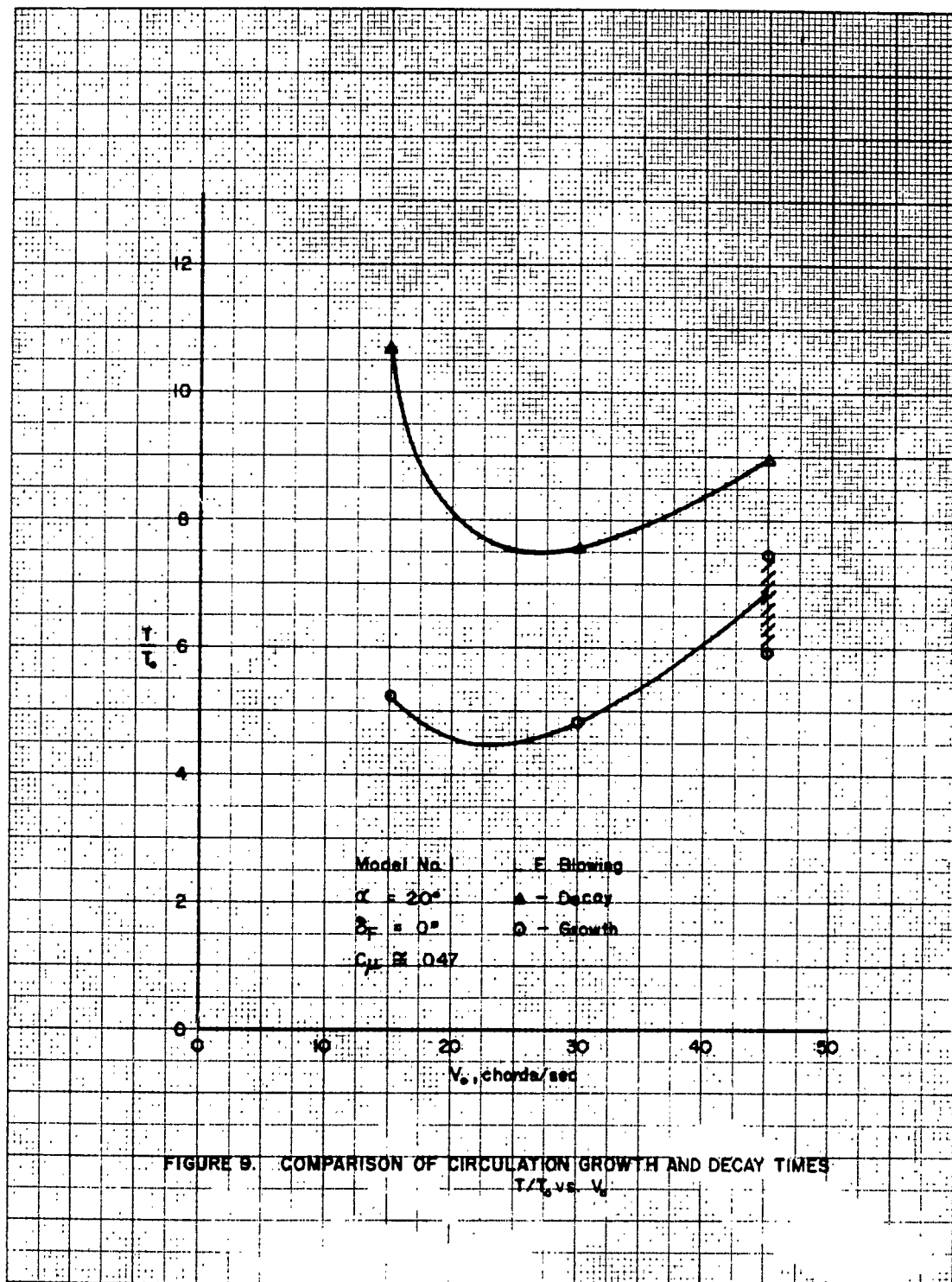
For comparison purposes, a series of tests of the inverse case, namely that of an airfoil with an operating BLC system which was suddenly

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23015 Airfoil
$\alpha = 20°$
$C_\mu \cong 0.047$
$V_o = 30$ chords/sec
L.E. Blowing

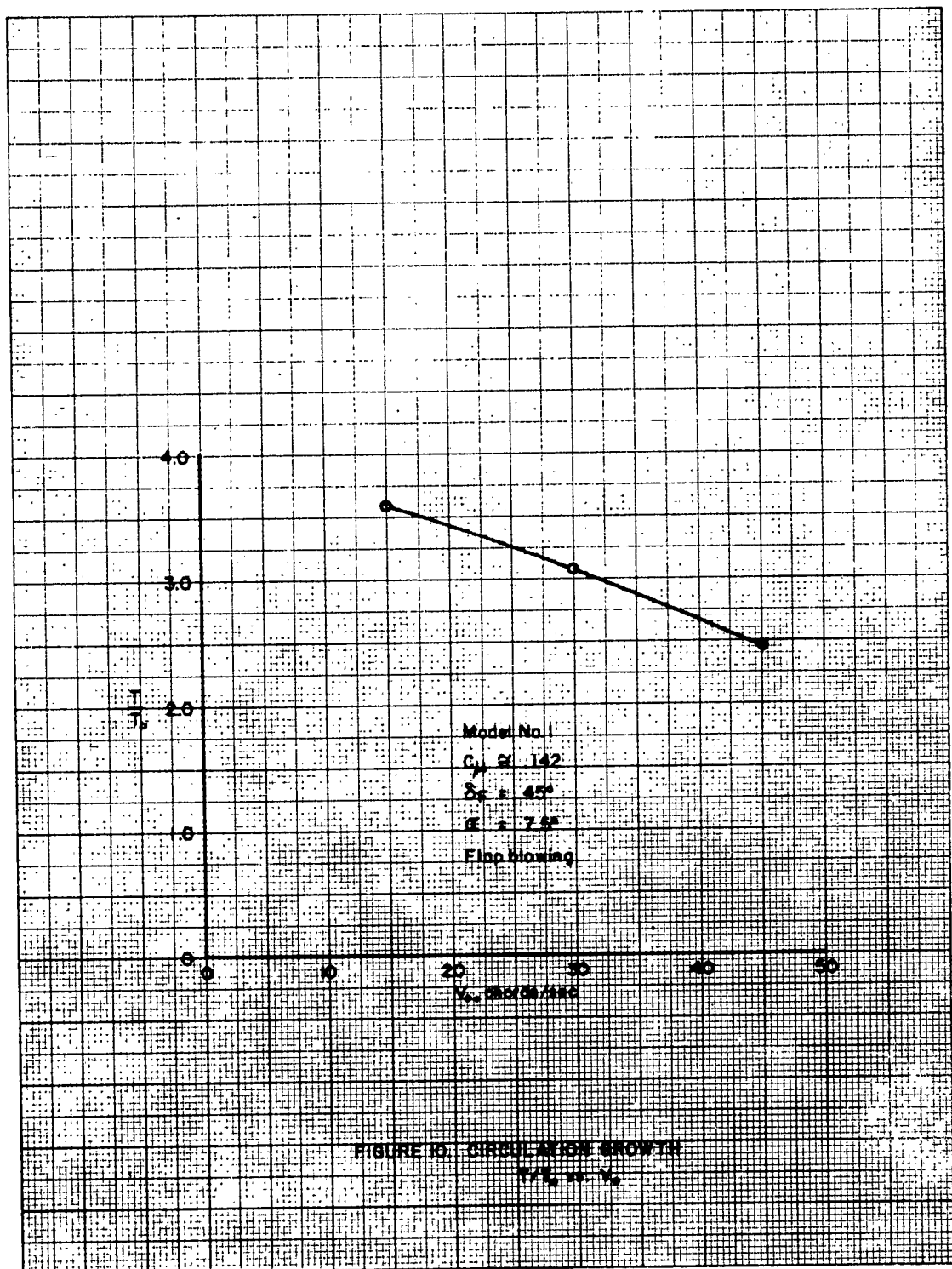FIGURE 8. CIRCULATION GROWTH TIME
T vs. δ_F

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interrupted, were conducted. The resulting times for circulation decay are compared with the times for circulation growth for the corresponding speeds, C_μ, and angle of attack in Figure 9. Since the traces showing the solenoid valve action indicated no particular difference between the length of time required to open and the length of time required to close, the conclusion is that the greater times required for circulation decay is a reflection of the inertia of the mass of air entrained by the blowing jet.

Since blowing over the flap could not increase the stalling angle of the wing, but on the contrary tended to reduce it, tests of the flap blowing were conducted at an angle of only 7.5°. With a flap deflection of 15° there was only a slight separation, so extensive tests were not conducted. With $\delta_f = 45^\circ$ the blowing jet had a much greater effect. As shown by Figure 10, the variation of the time required for circulation growth with forward speed was roughly of the same nature as for the previous cases, but much faster. The total change of circulation was of about the same order of magnitude, but because only the flap had suffered complete separation; the steady state value of the minimum C_μ required was much greater. On the other hand, the fact that the separated area extended only over the .20-chord flap undoubtedly accounted for the shorter time required for reattachment.
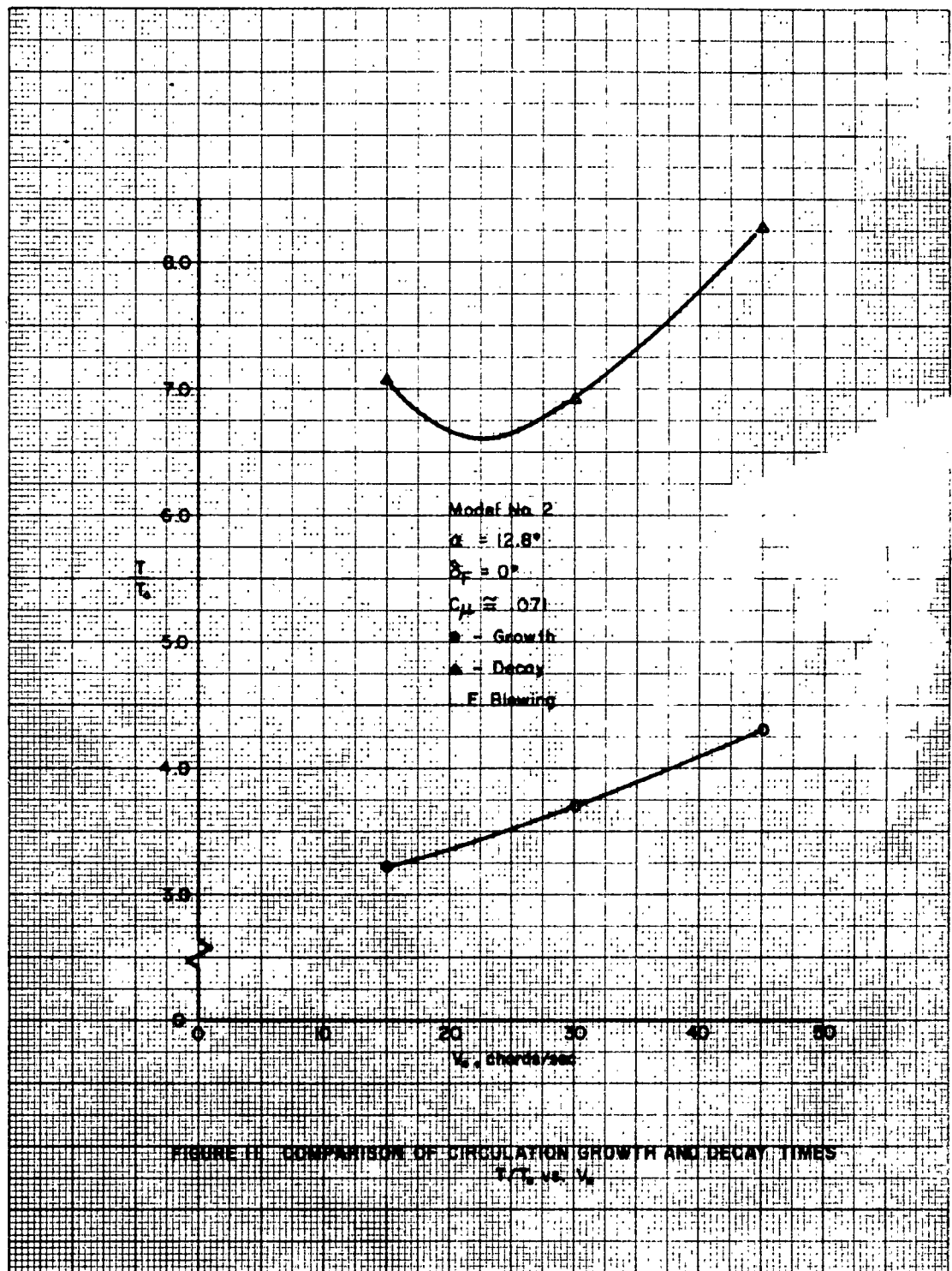
The NACA 65006 airfoil behaved in much the same manner as the thicker NACA 23015 section, except that the leading edge type of separation proved much more difficult to control. Stall of the basic airfoil occurred between 11° and 12°, and it proved impossible with the arrangement

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FIGURE 9. COMPARISON OF CIRCULATION GROWTH AND DECAY TIMES
T/T_o vs V_o

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FIGURE 10. CIRCULATION GROWTH
$\frac{T}{T_0}$ vs. V_0

Model No. 1
$C_\mu \cong .142$
$\delta_F = 45°$
$\alpha = 7.5°$
Flap blowing

$\frac{T}{T_0}$

V_0, knots/sec

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employed to exceed $\alpha = 12.8°$ even when employing a C_μ of as much as .071.
It was thought the different character of the separation, initiating as
it did from the leading edge, might explain the relatively short circula-
tion growth times shown in Figure 11, but further tests indicated that
it was merely a matter of the flow attachment not being complete. As
shown by Figure 12, as C_μ was increased, the circulation growth time (and
circulation) increased until it was comparable to the time required to
reattach the NACA 23015 profile.

The results of the tests on the NACA 65006 profile are presented
in Table 2.

FIGURE 11. COMPARISON OF CIRCULATION GROWTH AND DECAY TIMES
τ/τ_0 vs. V_s

FIGURE 12. CIRCULATION GROWTH TIME
T vs. C_μ

65006 Airfoil
$\alpha = 12.8°$
$\delta_F = 0°$
$V_o = 30$ chords/sec
L.E. Blowing

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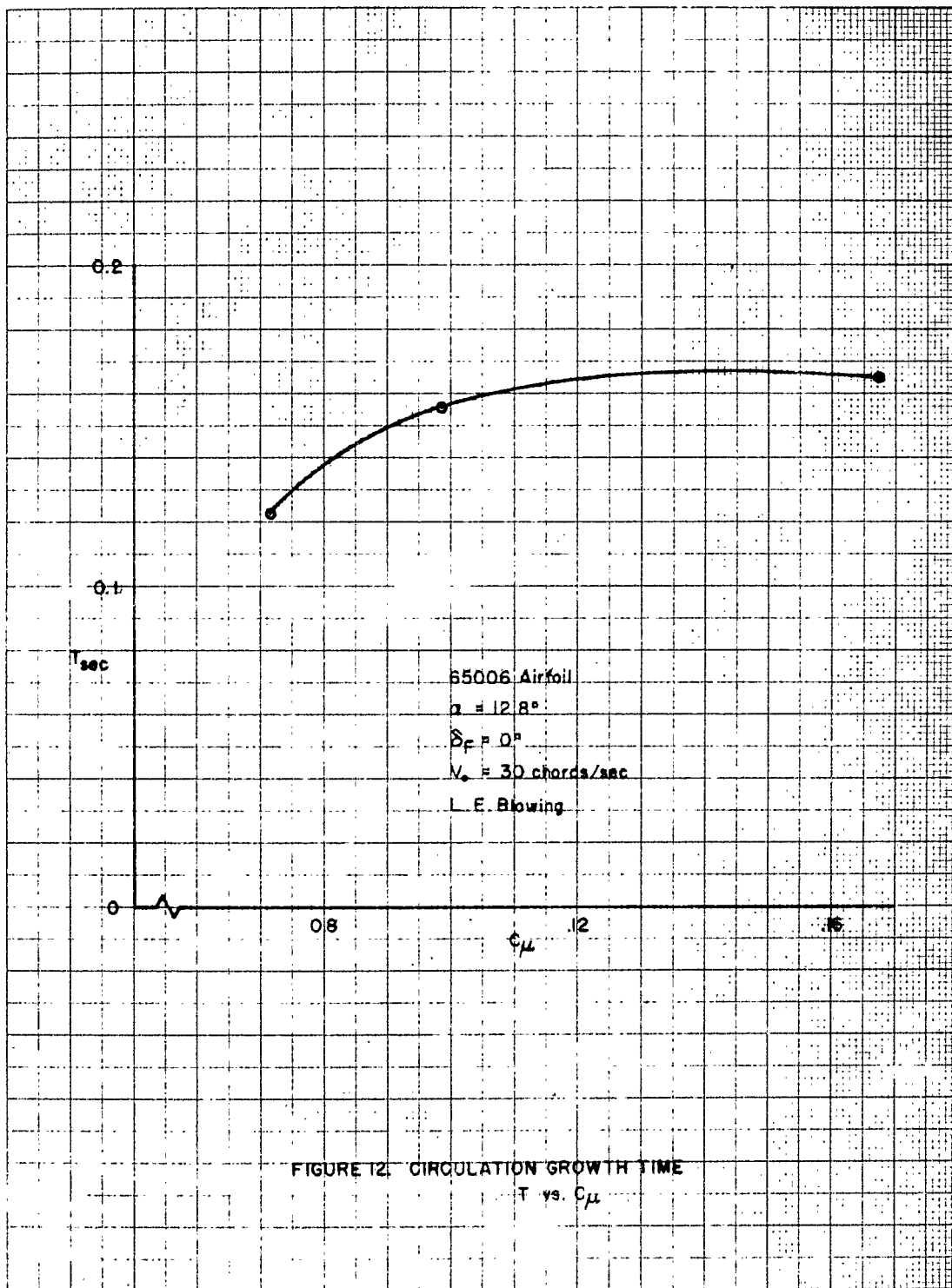
TABLE 2

Model No. 2   NACA 65006

	Run No.	a^o	$\delta_r{}^o$	V_o ft/sec	V_j ft/sec	V_o c/sec	T_o sec/c	T sec
1.	29	12.8	0	20	122.0	15	.0667	.216
2.	28	12.8	0	40	246.0	30	.0333	.123
3.	27	12.8	0	60	368.0	45	.0222	.096
4.	35	12.8	0	20	124.0	15	.0667	.471
5.	36	12.8	0	40	244.0	30	.0333	.229
6.	37	12.8	0	60	373.0	45	.0222	.184
7.	30	12.8	0	40	297.0	30	.0333	.156
8.	31	12.8	0	40	377.0	30	.0333	.166
9.	32	1.75	30	40	491.0	30	.0333	.115
10.	33	1.75	30	40	384.0	30	.0333	.115
11.	34	1.75	30	40	323.0	30	.0333	.111

TABLE 2 (Continued)

	T/T_0	C_μ	L.E.	T.E.	Growth	Decay	Initial C_l	Final C_l	ΔC_l
1.	3.24	.0701	x		x		.92	1.28	.36
2.	3.70	.0713	x		x		1.06	1.50	.44
3.	4.32	.0706	x		x		1.06	1.50	.44
4.	7.07	.0724	x			x	1.56	1.34	.22
5.	6.92	.0705	x			x	1.56	1.28	.28
6.	8.28	.0725	x			x	1.62	1.28	.34
7.	4.78	.1035	x		x		.92	1.50	.58
8.	4.99	.1670	x		x		.92	1.56	.64
9.	3.47	.4000		x	x		.96	2.14	1.18
10.	3.47	.2440		x	x		.94	2.20	1.26
11.	3.35	.1730		x	x		.92	2.00	1.18

CONCLUSIONS AND RECOMMENDATIONS

The results of this preliminary investigation clearly indicate that the smoke tunnel, when combined with high speed photographic techniques, is capable of providing unique information about unsteady flow phenomena. Further, it has shown that the time required for the growth or decay of circulation is dependent upon the extent of the separation existing without the application of boundary layer control and the type of boundary layer control applied. Except as an indication of the above factors, the total change of circulation level does not seem to control the growth or decay times, a given change of circulation being more rapidly achieved by blowing over the flap at a low angle of attack than by leading edge blowing at high angles. Another interesting point that emerged was the relative insensitivity of the leading edge system to increases of C_μ once reattachment had been achieved. This would not be expected in the case of flap blowing because, after reattachment, increases in C_μ produce pronounced jet flap effects causing continued increases in lift.

To improve the quality of the results obtained to date, the accuracy of certain measurements must be improved. More accurate free stream velocity measurements can be obtained by pulsing, at a known rate, one of the smoke streams visible in the camera field. Much more accurate blowing or suction information is required. About the only way this can be obtained is by utilizing a rake of static and total head tubes in the slot, each connected to a pressure transducer having a suitable response time. With such instrumentation, a detailed separation of the effect of

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the various parameters affecting the rate of circulation growth or decay could be obtained.

Although these measurements are of interest, they have just scratched the surface of an important and almost completely unknown segment of aerodynamics. With refinements of instrumentation, a great deal of detailed information could be obtained about a large variety of boundary layer control devices including those employing suction. Further, model mount changes could be incorporated in the smoke tunnel which would permit investigations of plunging or pitching models and the consequent isolation of such effects.

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control concepts as the U.S. Army Caribou airplane.

Continuation and expansion of future efforts before all flight tests, both in wind tunnel experiments and in scale model tests of the ballistics aspects, are fully warranted by the results and findings thus far.